Searching for BSM Higgs Signals at NLO

Fermilab
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Englert, MM: JHEP
Craig, Englert, MM: PRL
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Towards a Precision Higgs Era

- Higgs:
  - Unique opportunity to confront fundamental questions about nature.

- Why expect new physics?
  - Hierarchy problem
    - SUSY, Composite, Extra Dim, unknown solutions to hierarchy problem?
  - Dark matter:
    - Higgs portal, new EW states?
  - It might be there and we should look!

Towards a Precision Higgs Era

- Higgs:
  - Unique opportunity to confront fundamental questions about nature.

- In practice:
  - Need to determine all properties (couplings/higher dim) as best as possible.
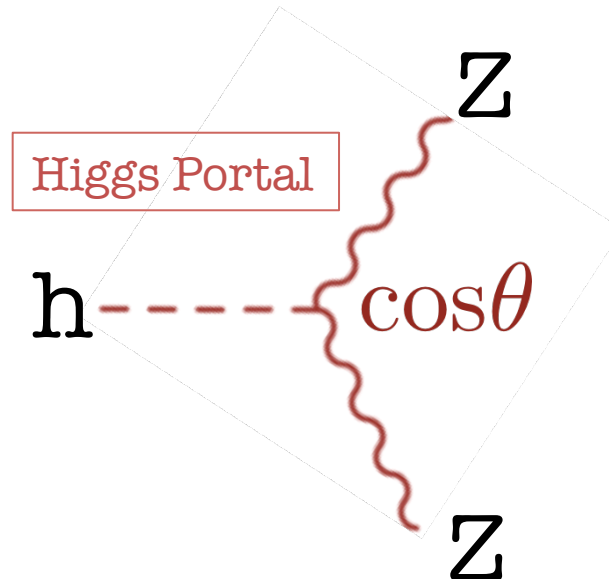
- What should we look for?

LO BSM Higgs Signals

- Tree level?

  - Already know where to look:
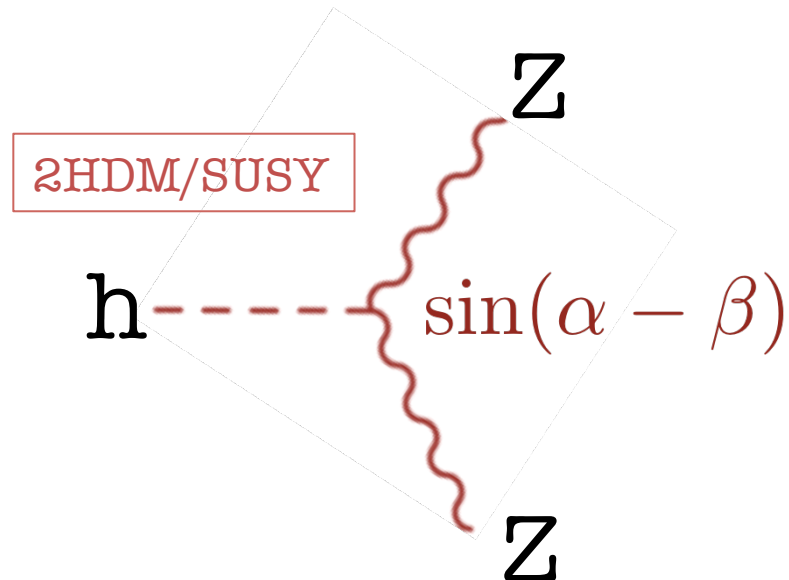
LO BSM Higgs Signals
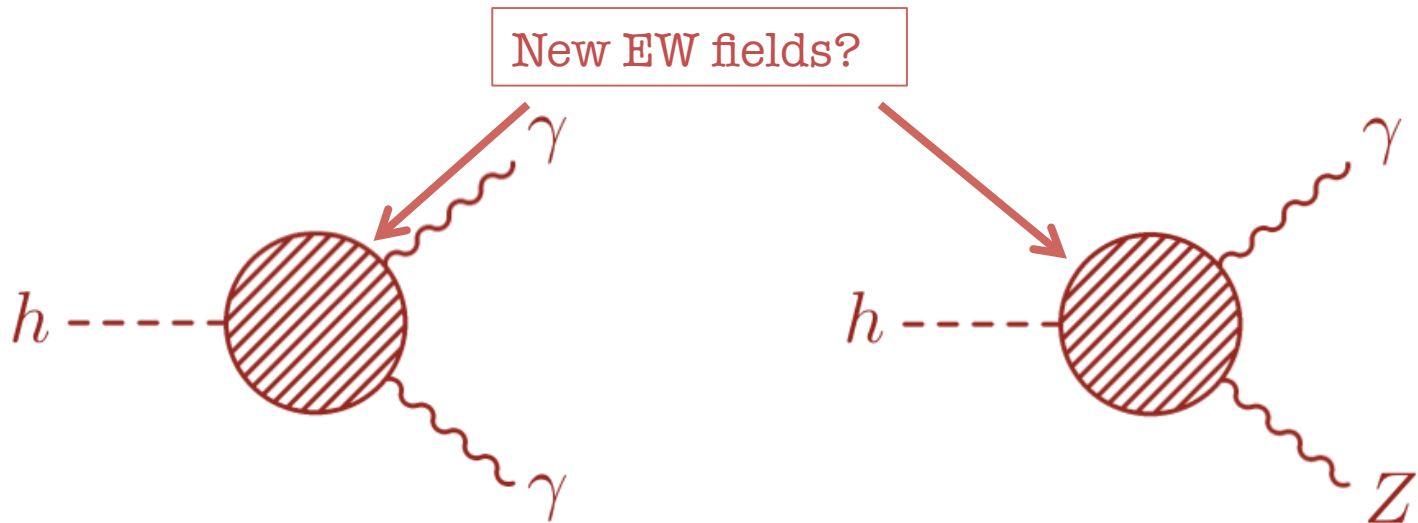
- Tree level?
  - Already know where to look:

LO BSM Higgs Signals

- Tree level?
  - Only if Higgs mixed with new scalar...

  - No tree level: new fields charged under additional symmetry (Lorentz/global/gauge)
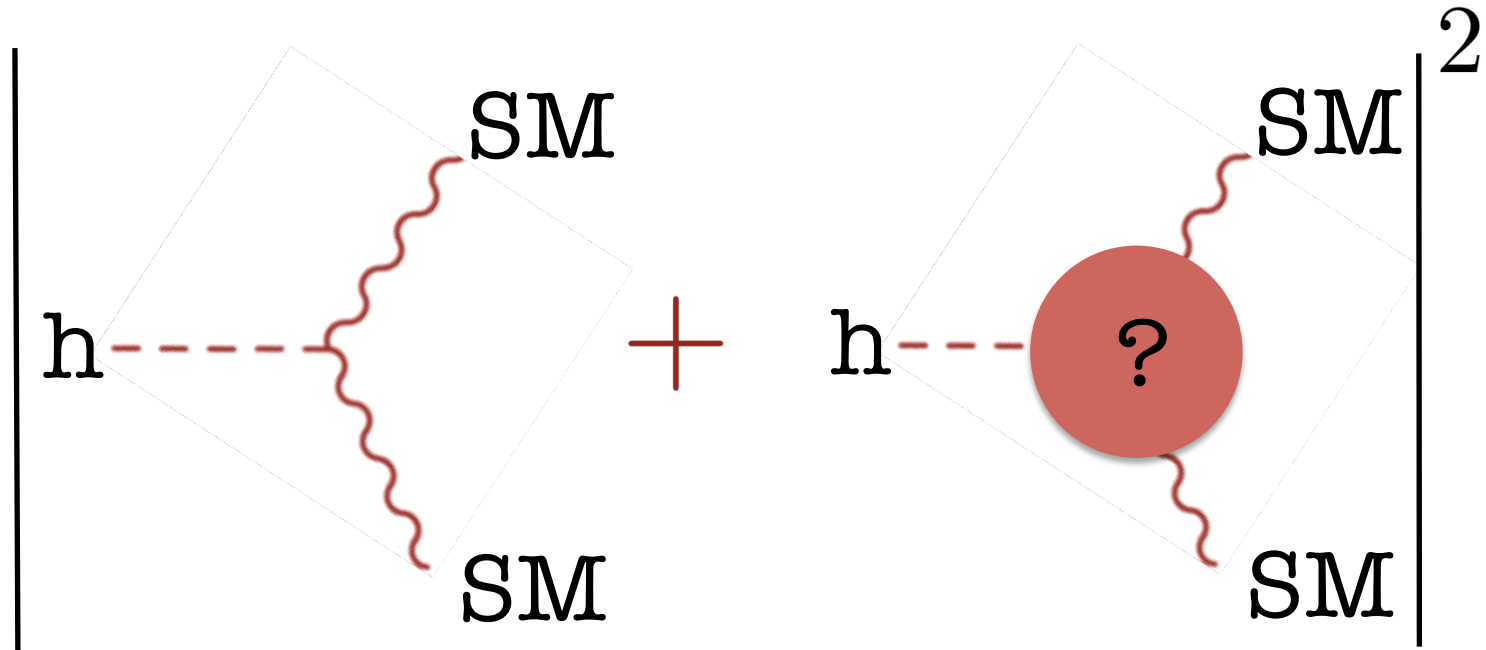
  - Only at loop level in this case!

LO BSM Higgs Signals

- Loop level?
  - Already know where to look:

New EW fields?

  - Former has received a **LOT** of attention
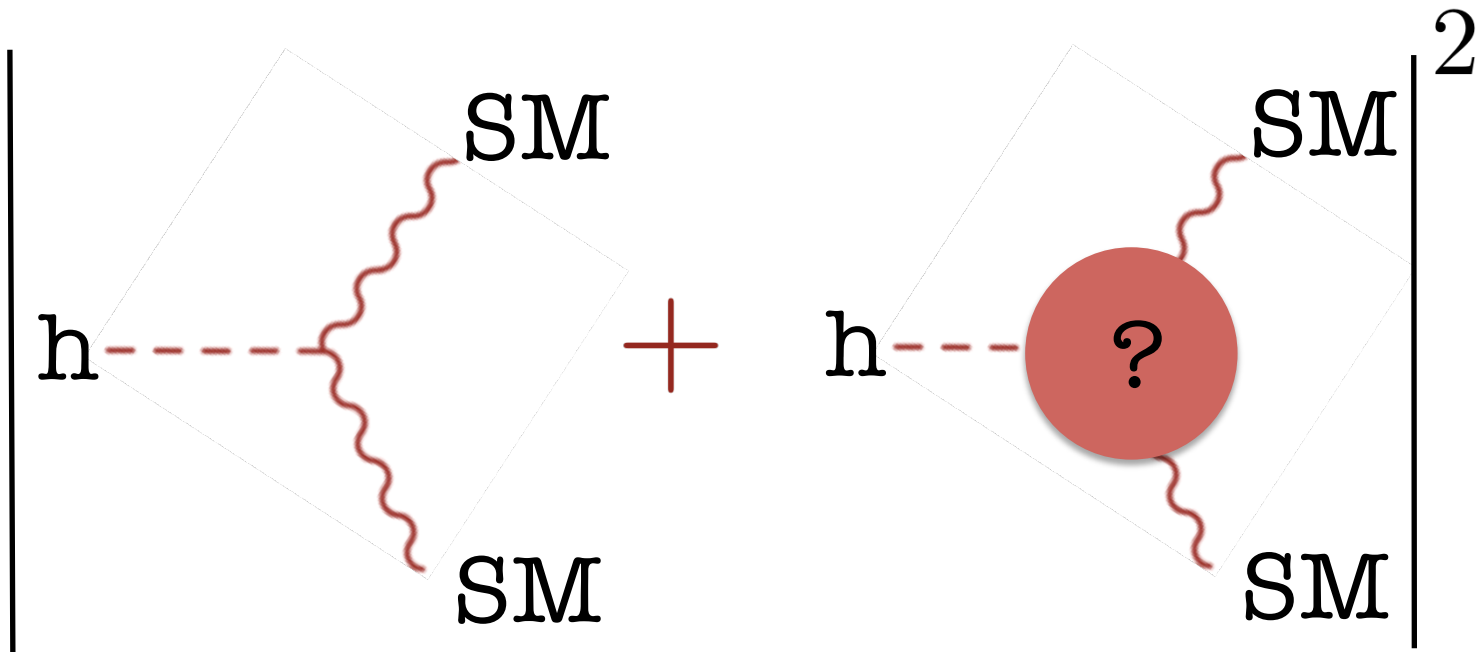 - Finite: straightforward to calculate

NLO BSM Higgs Signals

- Loop level?
  - Almost entirely unexplored!

$$\left| \begin{array}{c} \text{SM} \\ h \\ \text{SM} \end{array} \right. + \left. \begin{array}{c} \text{SM} \\ h \quad ? \\ \text{SM} \end{array} \right|^2$$

  - Def: LO amplitude (whatever loop-level) SM-like, new physics enters at NLO.

NLO BSM Higgs Signals

- Loop level?
  - Almost entirely unexplored!

$$\left| \quad \text{SM} \atop h - - - \atop \text{SM} \quad + \quad h - - - \text{?} \atop \text{SM} \right|^2$$

  - Very generic possibility...
  - But what should we look for?
  - NLO ➜ small, so best bet: best accuracy.

Higgs Couplings: Future

- What about LHC + 250 GeV LC?
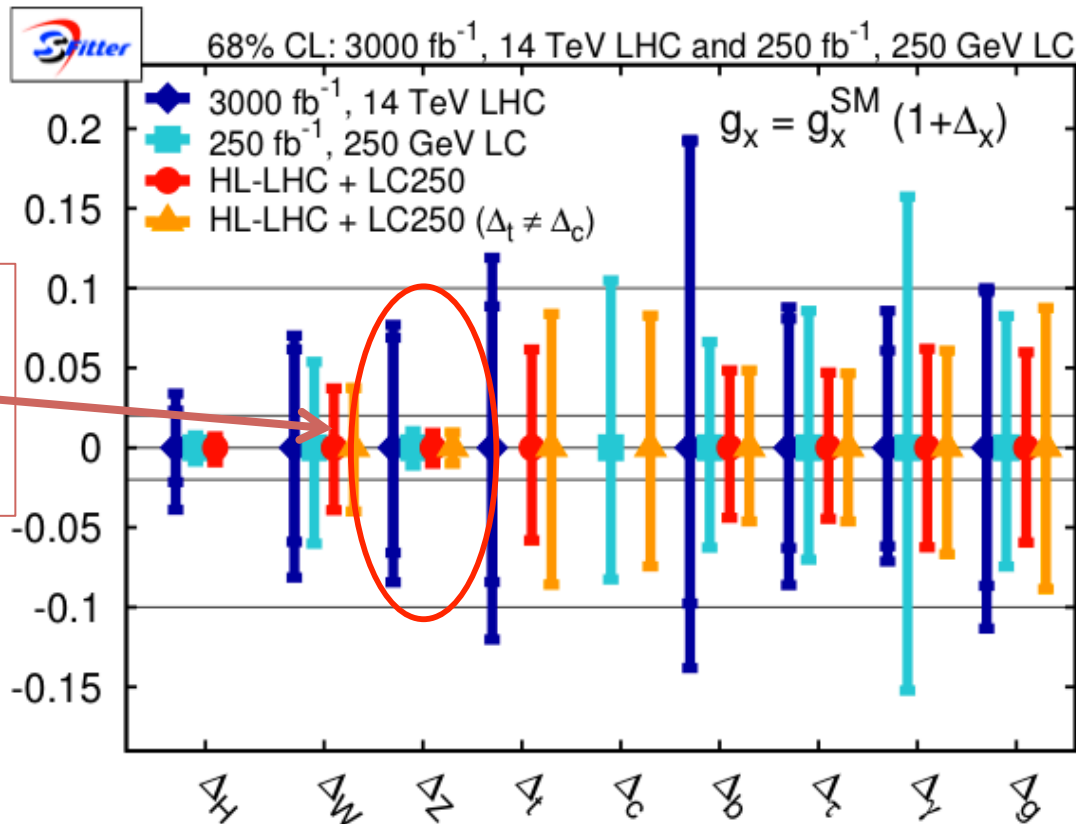
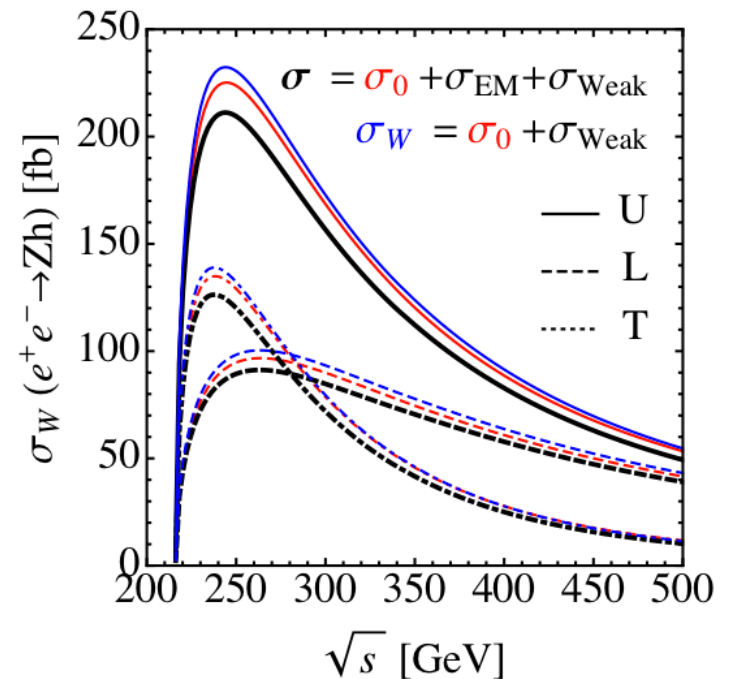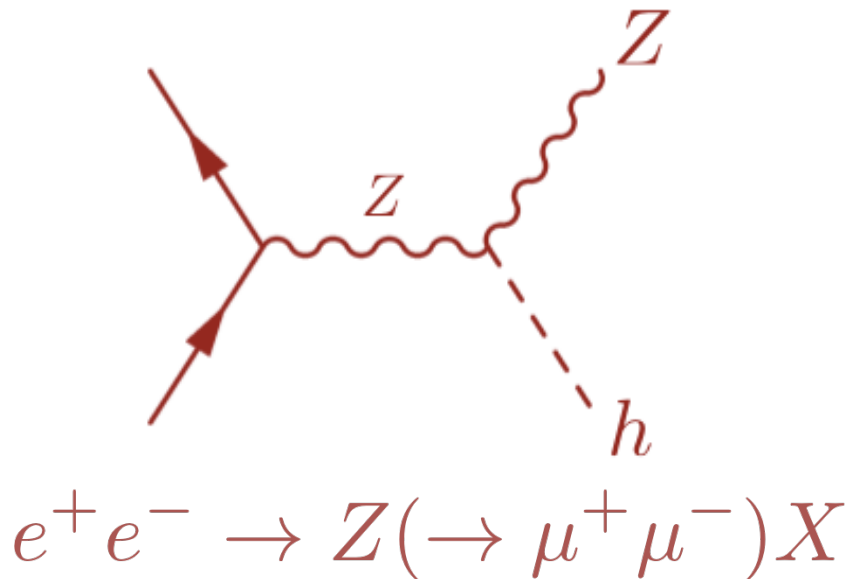- LHC accuracy similar for other couplings

Higgs Couplings: Future

- At LC Z-coupling is special. Why?
  - 250 GeV Associated Production dominant:

$$e^+e^- \rightarrow Z(\rightarrow \mu^+\mu^-)X$$

- Measure Z-recoils alone
  - Determine coupling independent of Higgs decays!

Associated Production: BSM

- ## What precision to expect?

$$\delta(\sigma_{Zh}) = 2\delta(g_Z)$$

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5 - 7\%$	$2 - 5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6 - 8\%$	$3 - 5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4 - 6\%$	$2 - 5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4 - 6\%$	$2 - 4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6 - 8\%$	$2 - 5\%$	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	$10 - 13\%$	$4 - 7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14 - 15\%$	$7 - 10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

Higgs Snowmass report 2013.

Associated Production: BSM

- Great testing ground for NLO ideas
  - Need to calculate:

$$2 \, \text{Re} \left[\quad \cdot \quad \right]$$
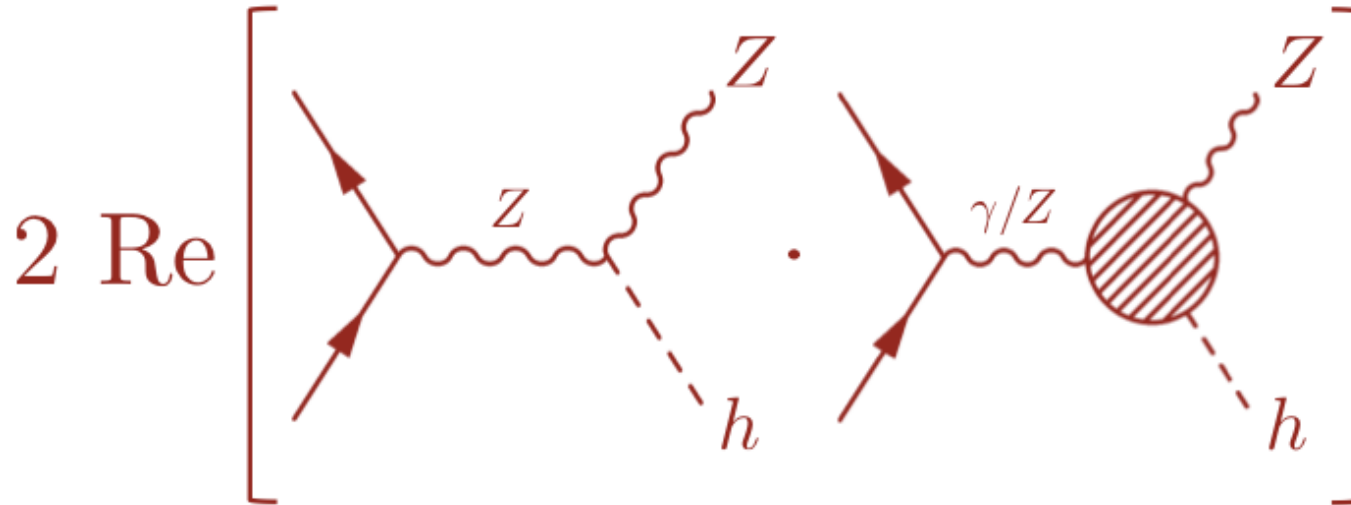
  - Magnitude of corrections?
    - Try specific models first

Models: Inert 2HDM

- "Inert" Two Higgs doublet model

$$V \supset m_\phi^2 |\phi|^2 + \lambda |H|^2 |\phi|^2 + \lambda' |H \cdot \phi^\dagger|^2$$
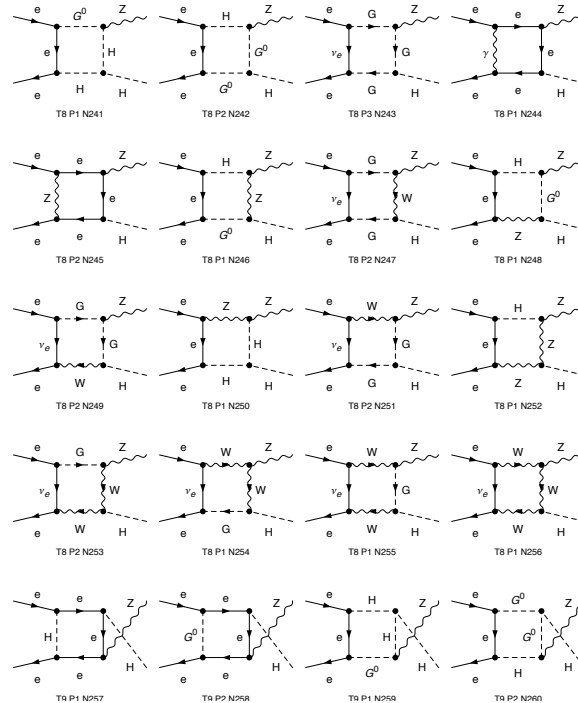
Charged under
approximate symmetry

- No tree-level modifications

- Trade these parameters for more intuitive set:

  - Charged scalar mass: m_{ϕ_+}
  - Charged scalar tri-linear coupling to Higgs: A_{ϕ_+}
  - Charged-neutral mass-splitting: Δ_ϕ

- Where we define $\Delta_\phi = m_{\phi_0} - m_{\phi_+}$

Models: Inert 2HDM

- "Inert" Two Higgs doublet model

$$V \supset m_\phi^2 |\phi|^2 + \lambda |H|^2 |\phi|^2 + \lambda' |H \cdot \phi^\dagger|^2$$

- Using Feynarts/Formcalc/Looptools calculate SM@NLO

$\times 23$

Models: Inert 2HDM

- "Inert" Two Higgs doublet model

$$V \supset m_\phi^2 |\phi|^2 + \lambda |H|^2 |\phi|^2 + \lambda' |H \cdot \phi^\dagger|^2$$

- Using Feynarts/Formcalc/Looptools calculate and the new physics contributions:
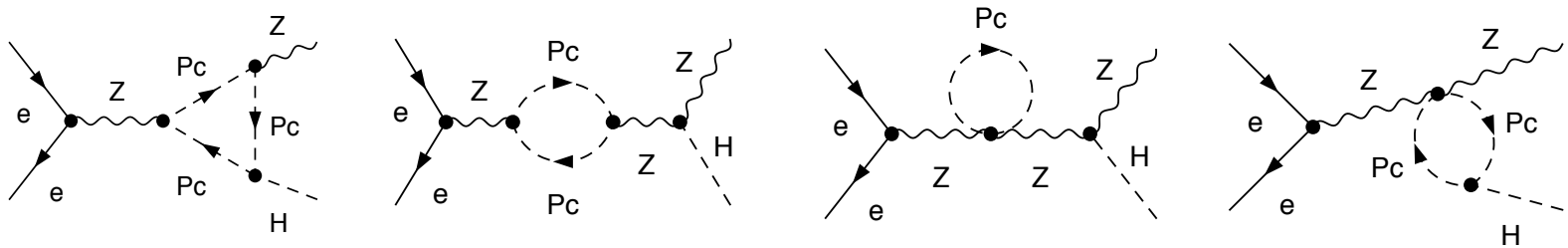
- Also, calculate the 2-point functions necessary for Peskin-Takeuchi...

Results: Parameterization

- Define two parameters

  – Correction to associated production:

  $$\delta\sigma_{Zh} = \frac{\sigma_{BSM}(e^+e^- \to Zh) - \sigma_{SM}(e^+e^- \to Zh)}{\sigma_0(e^+e^- \to Zh)}$$

  – Corrections to diphoton Higgs decay

  $$R_{h\gamma\gamma} = \frac{\Gamma_{BSM}(h \to \gamma\gamma)}{\Gamma_{SM}(h \to \gamma\gamma)} = \frac{\mathrm{BR}_{BSM}(h \to \gamma\gamma)}{\mathrm{BR}_{SM}(h \to \gamma\gamma)} \left[\frac{\Gamma^{\mathrm{tot}}_{BSM}}{\Gamma^{\mathrm{tot}}_{SM}}\right]^{-1}$$
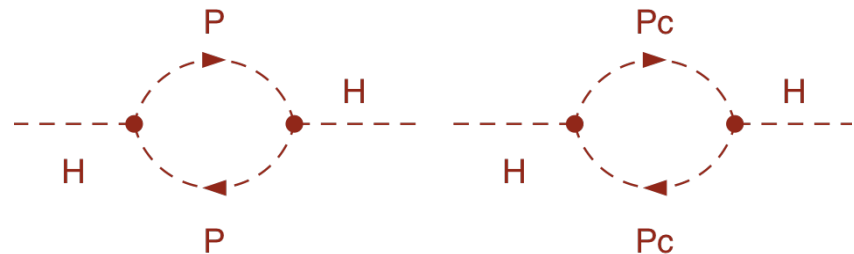
Results: Inert Doublet
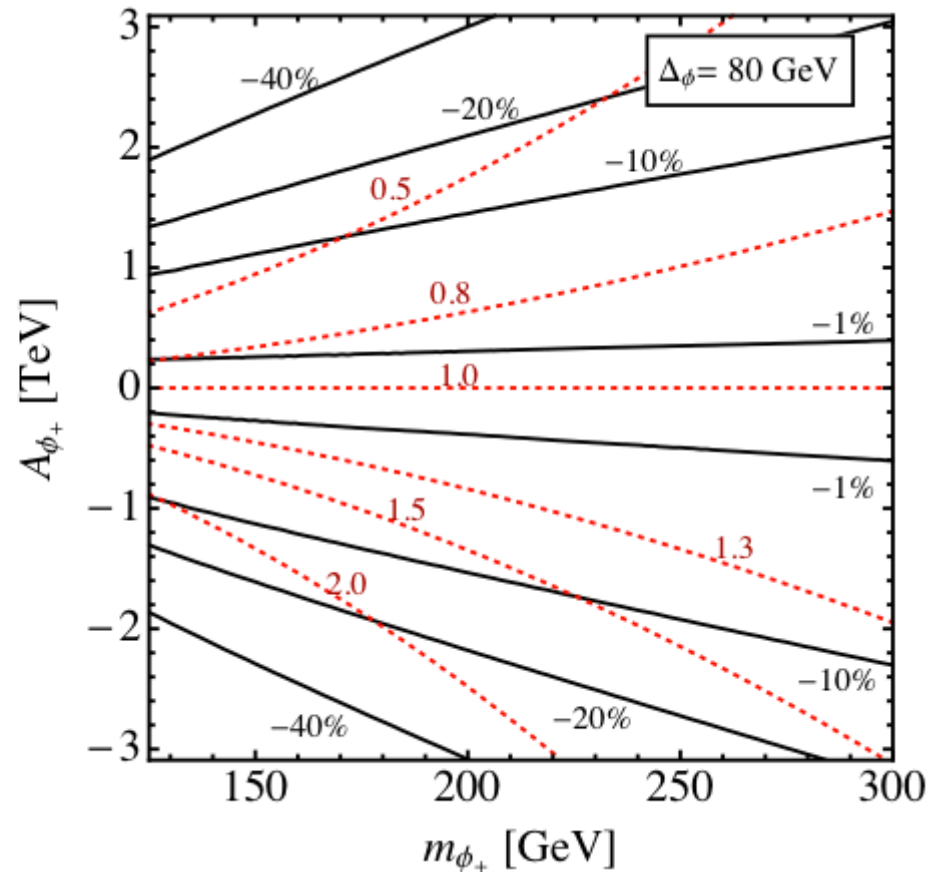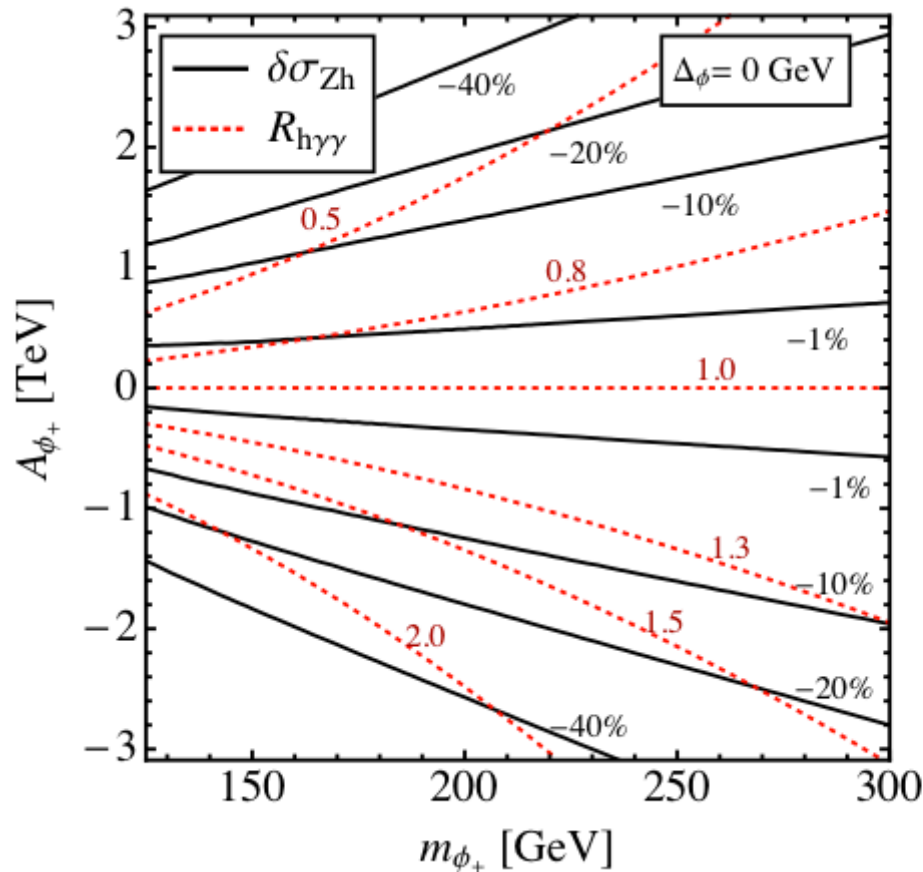
- As expected, corrections to associated production may be observable!

Results: Inert Doublet

- Corrections mostly quadratic in coupling:
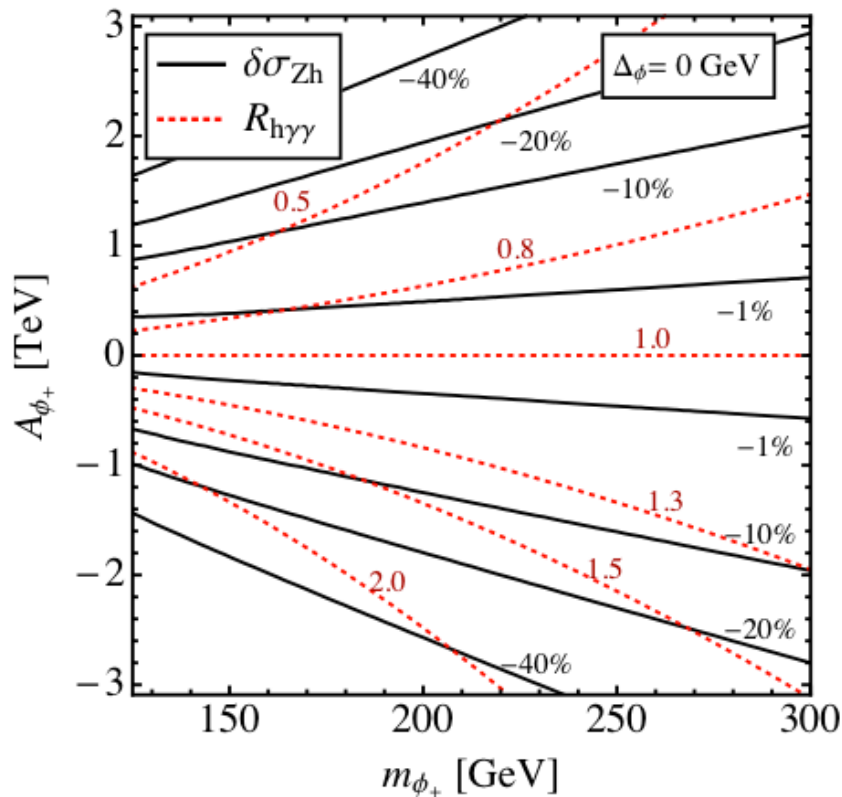
Only the Higgs wave-function renormalization correction scales in this way!

- EW gauge corrections subdominant!
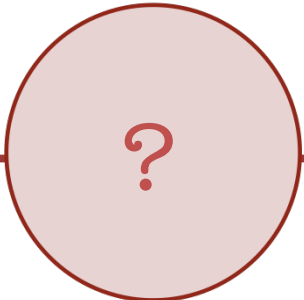 – Remember this...

What About Fundamental Ideas?

- Naturalness under scrutiny:

$$h \; \text{---} \; \Lambda \; \text{---} \; h \quad \neq \Lambda^2$$

- We know some natural theories:
  - SUSY
  - Composite....

- Common feature: Top Partners!

What is Naturalness?

- Pragmatically: No quadratic divergences.
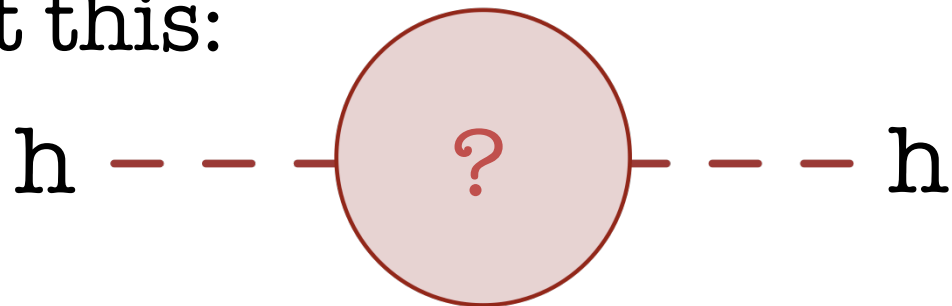
$$\text{h} \text{ -- -- --} \bigcirc{?} \text{-- -- --} \text{h} \quad \neq \Lambda^2$$

- LHC: SUSY/Stop/KK/t' searches...

- Explore naturalness generally?
  - Must we commit to specific UV-completions?

Generalizing Naturalness

- Staring at this:

$$h\ {-}\ {-}\ {-}\ {-}\ \boxed{?}\ {-}\ {-}\ {-}\ {-}\ h$$

- Scalars:

$$\mathcal{L}_{\text{Nat}} = \sum_i \left(|\partial_\mu \phi_i|^2 - m_i^2 |\phi_i|^2 - \lambda_i |H|^2 |\phi_i|^2 \right)$$

- Coupling is fixed: $\displaystyle\sum_i \lambda_i = 6\lambda_t^2$

- Captures dominant top-partner-Higgs interactions!

Generalizing Naturalness

- Scalars:

$$\mathcal{L}_{\mathrm{Nat}} = \sum_i \left(|\partial_\mu \phi_i|^2 - m_i^2 |\phi_i|^2 - \lambda_i |H|^2 |\phi_i|^2 \right)$$

- Coupling is fixed: $\sum_i \lambda_i = 6\lambda_t^2$

- Captures aspects of naturalness!

  – Specifically: Any solution to the hierarchy problem with scalar top partners will have **at least** these fields with these couplings.

  – First: Assuming gauge singlets.

Physical Effects

- Staring at this:

$$\delta m_h^2 = \;\; \text{h} \; - - - \bigcirc\!\!? \; - - - \; \text{h}$$

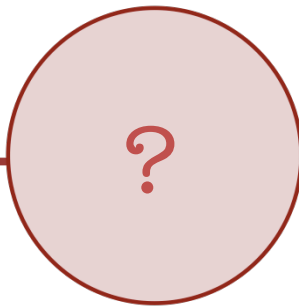# Physical Effects

- Staring at this:

$$\delta m_h^2 = \text{h} \,\text{---}\,\text{---}\,\text{---}\, \boxed{?} \,\text{---}\,\text{---}\, \text{h}$$

Frequently discussed

Physical Effects

- Staring at this:

$$\delta Z_h = \text{h} \ {-} \ {-} \ {-}\!\!\!\bigcirc\!\!\!\!\!\!?\!\!\!\!\!\!\bigcirc\ {-} \ {-} \ {-}\ \text{h}$$

Physical Effects

- Staring at this:

$$\delta Z_h = \text{h} - - - - \bigcirc{?} - - - \text{h}$$

Never discussed

Physical Effects

- Staring at this:

$$\delta Z_h = \mathtt{h} \; - - - - \bigcirc{?} - - - \mathtt{h}$$

- Is it physical? Integrating out:

$$\mathcal{L}_{eff} = \frac{c_H}{m_\phi^2} \left(\frac{1}{2} \partial_\mu |H|^2 \partial^\mu |H|^2 \right) + \dots$$

Physical Effects

- Staring at this:

$$\delta Z_h = \; \texttt{h} \; \text{-- -- --} \; \bigcirc{?} \; \text{-- -- --} \; \texttt{h}$$

- Is it physical?

$$\mathcal{L} \supset \left(1 + 2v^2 \frac{c_h}{m_\phi^2} \right) \frac{1}{2} \partial_\mu h \partial^\mu h$$

$$+ m_W^2 W^+ W^- + \frac{\sqrt{2}}{v} m_W^2 h W^+ W^- + ...$$

Physical Effects

- Staring at this:

$$\delta Z_h = \quad \text{h} \; - - - - \bigcirc\!? \; - - - \text{h}$$

- Is it physical?

$$\mathcal{L} \supset \left(1 + 2v^2 \frac{c_h}{m_\phi^2}\right) \frac{1}{2}\partial_\mu h \partial^\mu h$$

Rescaling pulls correction into all other couplings

$$+ m_W^2 W^+ W^- + \frac{\sqrt{2}}{v} m_W^2 h W^+ W^- + \ldots$$

Physical Effects

- Staring at this:

$$\delta Z_h = \ \mathtt{h} \ \text{-} \ \text{-} \ \text{-} \ \boxed{?} \ \text{-} \ \text{-} \ \text{-} \ \mathtt{h}$$

- Is it physical?

$$\mathcal{L}_{eff} = \frac{c_H}{m_\phi^2}\left(\frac{1}{2}\partial_\mu|H|^2 \partial^\mu|H|^2\right) + \ldots$$

- Yes! $\delta c_{hVV} = \delta c_{h\bar{f}f} = c_H v^2/m_\phi^2$

Physical Effects

- But... naturalness: $m_\phi \sim v$

- Need the full calculation, e.g:
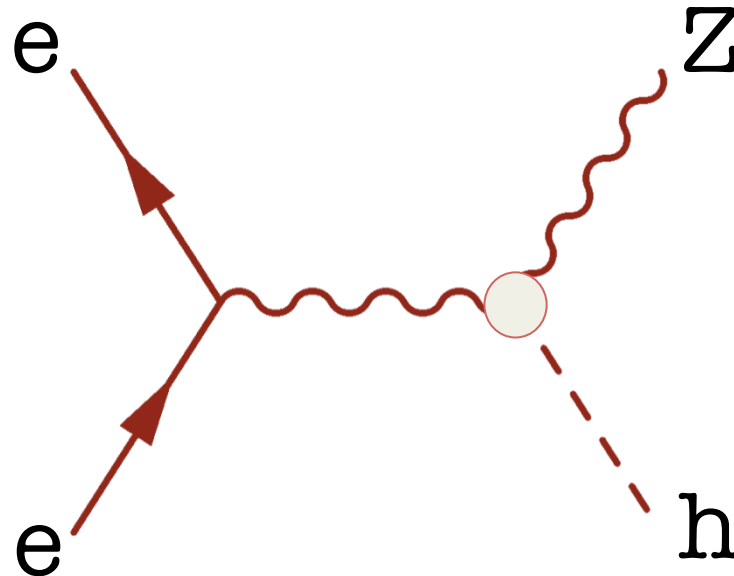
- Correction enters via counter-terms.

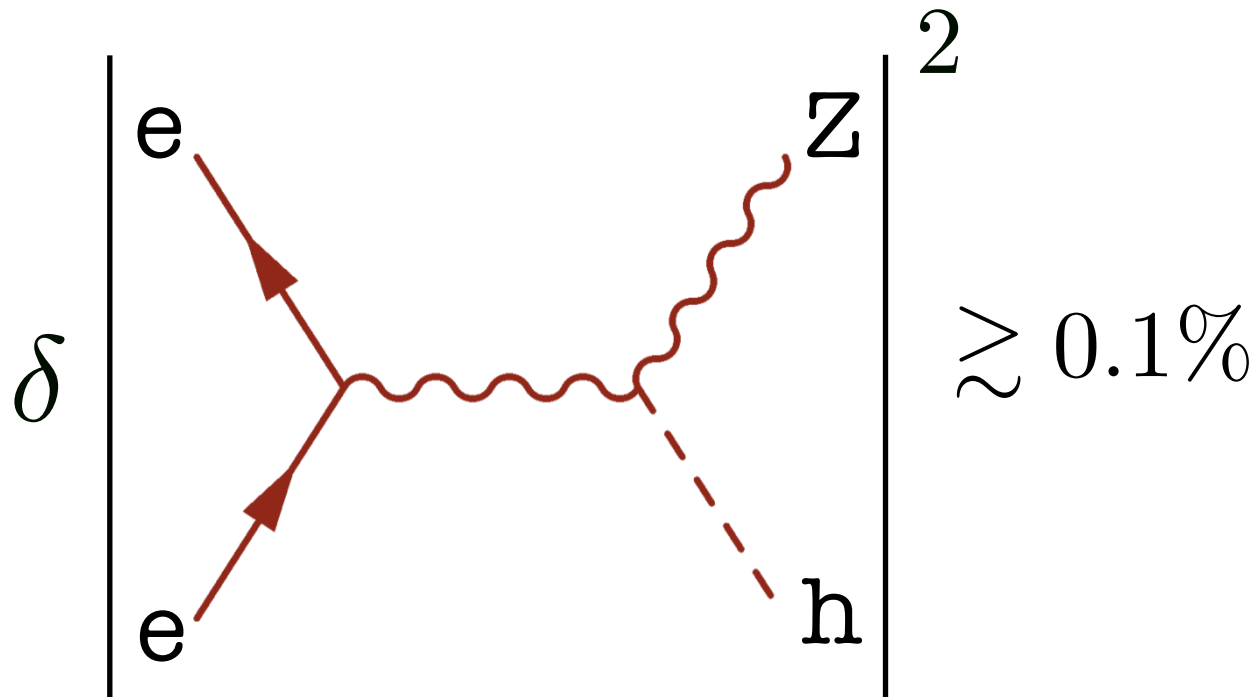# Measuring Naturalness

- If you happen to care…

$$\delta c_{hVV} = \frac{9\lambda_t^2 m_t^2}{4\pi^2 n_\phi m_h^2} \left(1 + F\left(\frac{m_h^2}{4m_\phi^2} \right) \right)$$

- Where:

$$F(\tau) = \frac{1}{4\sqrt{\tau(\tau - 1)}} \log \left(\frac{1 - 2\tau - 2\sqrt{\tau(\tau - 1)}}{1 - 2\tau + 2\sqrt{\tau(\tau - 1)}} \right)$$

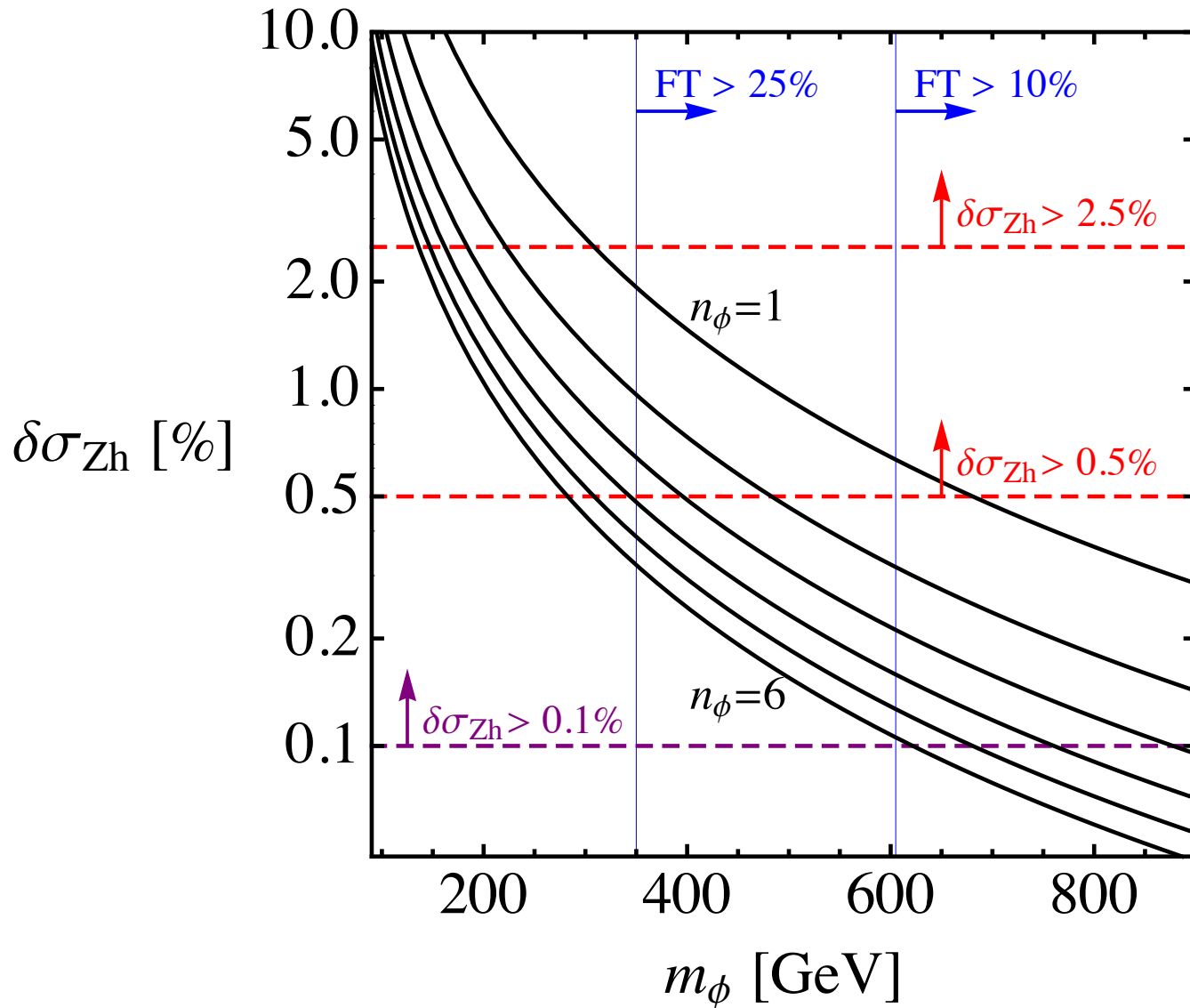# Measuring Naturalness

- LC offers extraordinary precision!

$$\delta \left| \begin{matrix} e & & Z \\ & & \\ & & \\ e & & h \end{matrix} \right|^2 \gtrsim 0.1\%$$

- Never say never for LHC too...

Measuring Naturalness

- Can a LC probe naturalness?
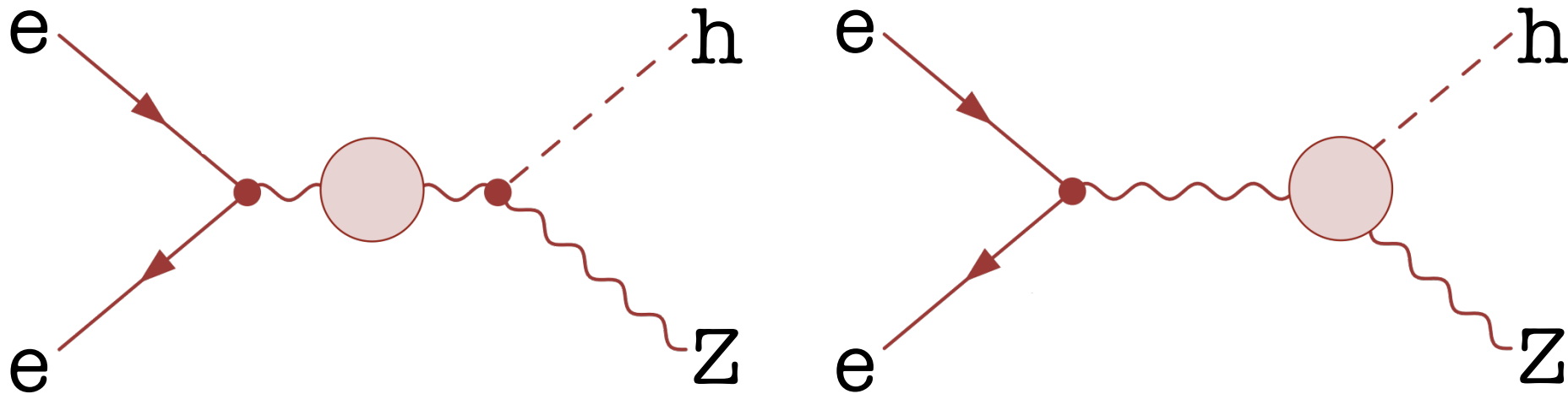
Measuring Naturalness

Yes.

Measuring Naturalness

$\delta\sigma_{Zh}$ [%]

FT > 25%

FT > 10%

$\delta\sigma_{Zh} > 2.5\%$

$n_\phi=1$

$\delta\sigma_{Zh} > 0.5\%$

$\delta\sigma_{Zh} > 0.1\%$

$n_\phi=6$

m_ϕ [GeV]

This plot for gauge singlet top partners.

Think: Twin Higgs models.
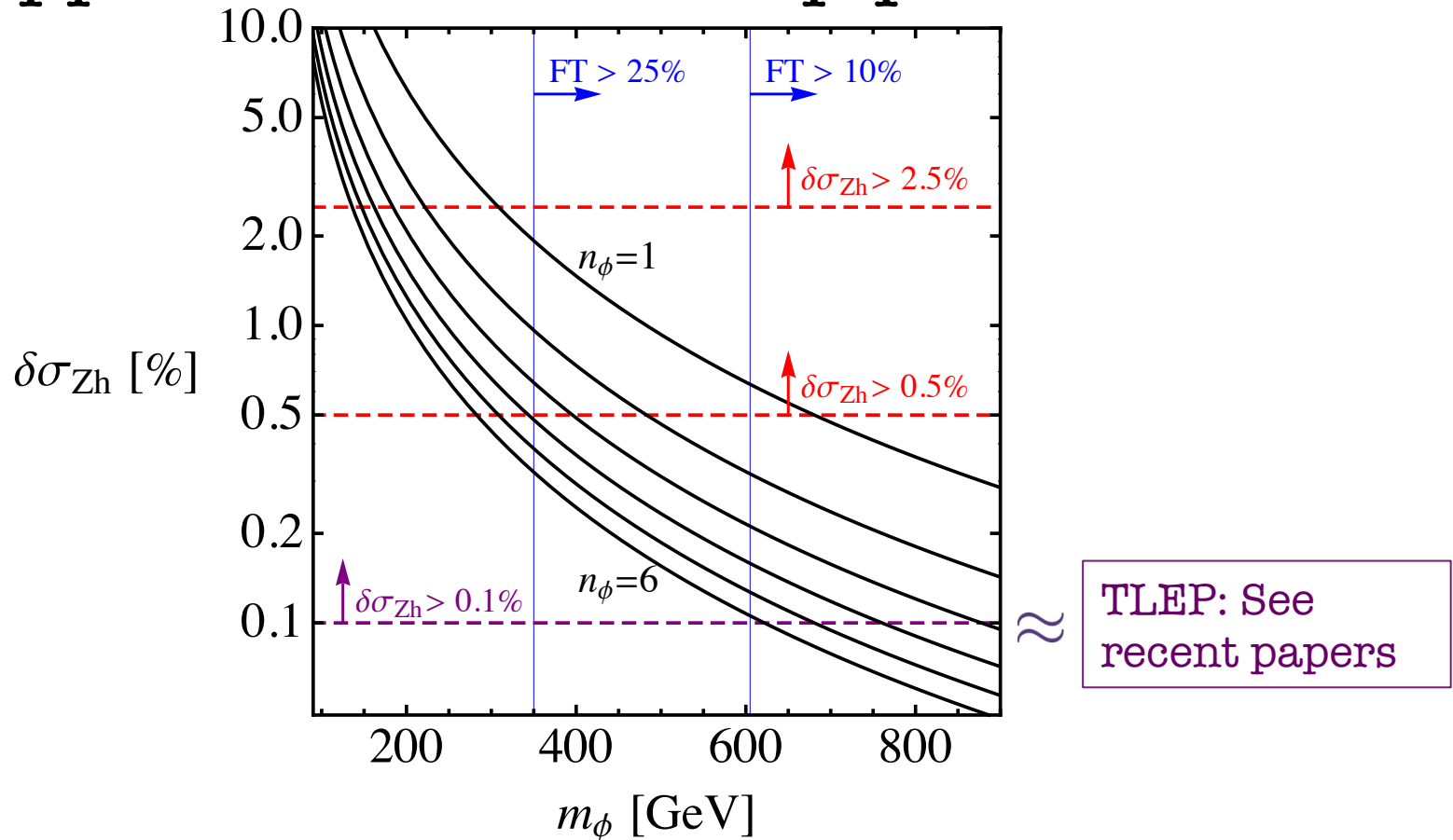
TLEP: See recent papers

Measuring Naturalness

- What if top-partners have EW charges?

- Result still dominated by WF correction!
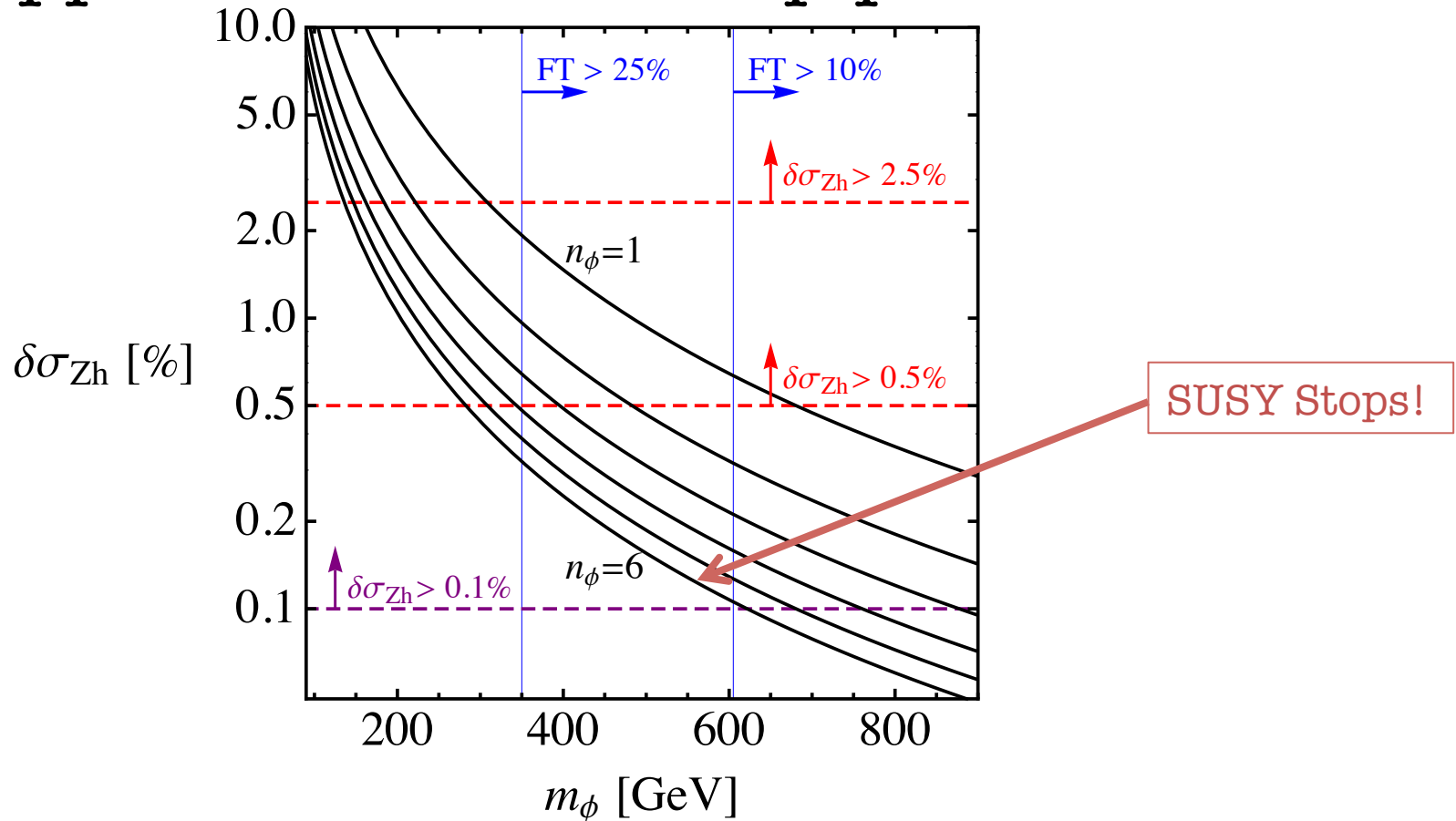 – C. Englert and M. M. $(\lambda_t^2 \gg g^2, g'^2)$

Measuring Naturalness

- Applies to all scalar top-partners:

- Regardless of gauge charges!

Measuring Naturalness

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- Regardless of gauge charges!

Measuring Naturalness

- Known Natural Theories:
  – SUSY, Composite, Technicolor, UEDs, RS,...
- Under some tension from LHC!

- But weak scale may still be natural
  – Flipped SUSY, Twin Higgs, SUSY with hidden stops,...!

- If, so what are generic predictions?

Measuring Naturalness

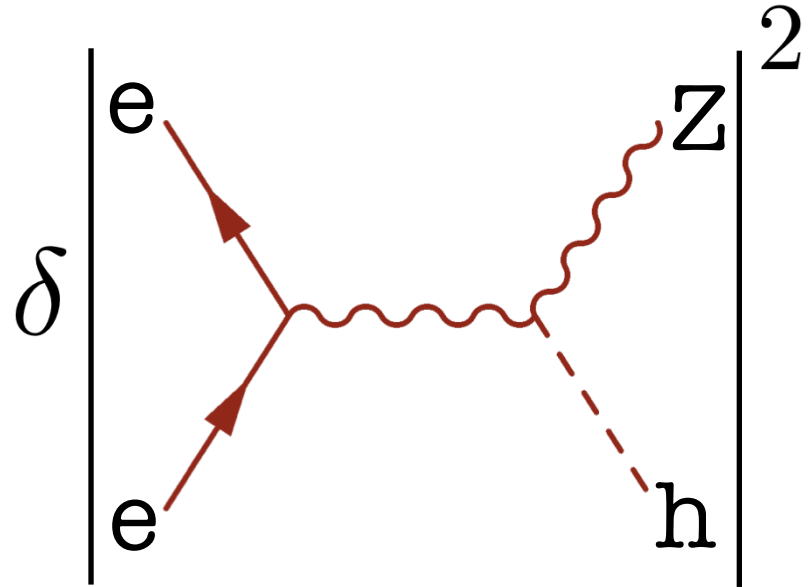- Goal: Distill Higgs physics from naturalness and test it!

- Lepton Collider:

$$\delta \left| \begin{matrix} e & & Z \\ & & \\ & & \\ e & & h \end{matrix} \right|^2$$
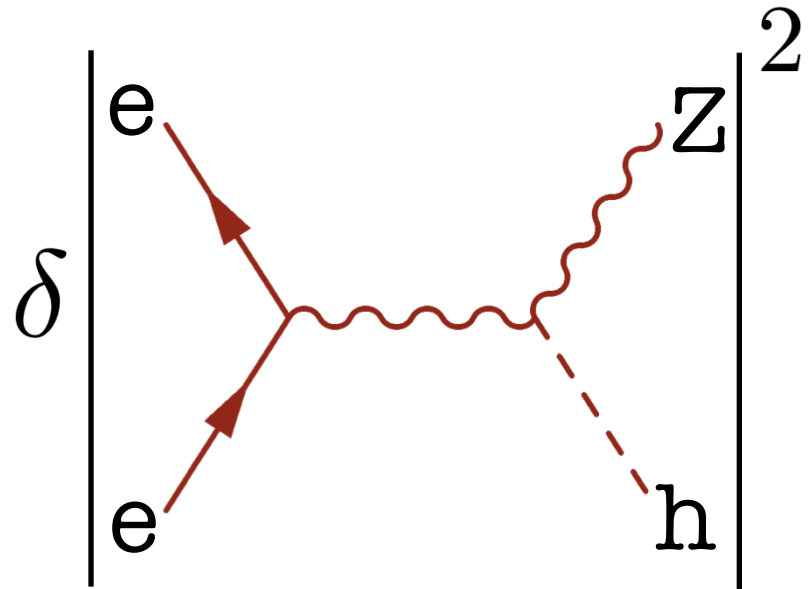
enables exploration of naturalness principle, independent of specific models!

Measuring Naturalness

- Goal: Distill Higgs physics from naturalness and test it!

- Lepton Collider:

$$\delta \left| \begin{matrix} e & & Z \\ & & \\ e & & h \end{matrix} \right|^2$$

...No fail theorem for naturalness!

BSM@NLO@LHC

- Only applicable to lepton collider?

- Naively: NLO effects typically too small

- Less naively: LHC makes lots of Higgs, can probe tails of distributions.

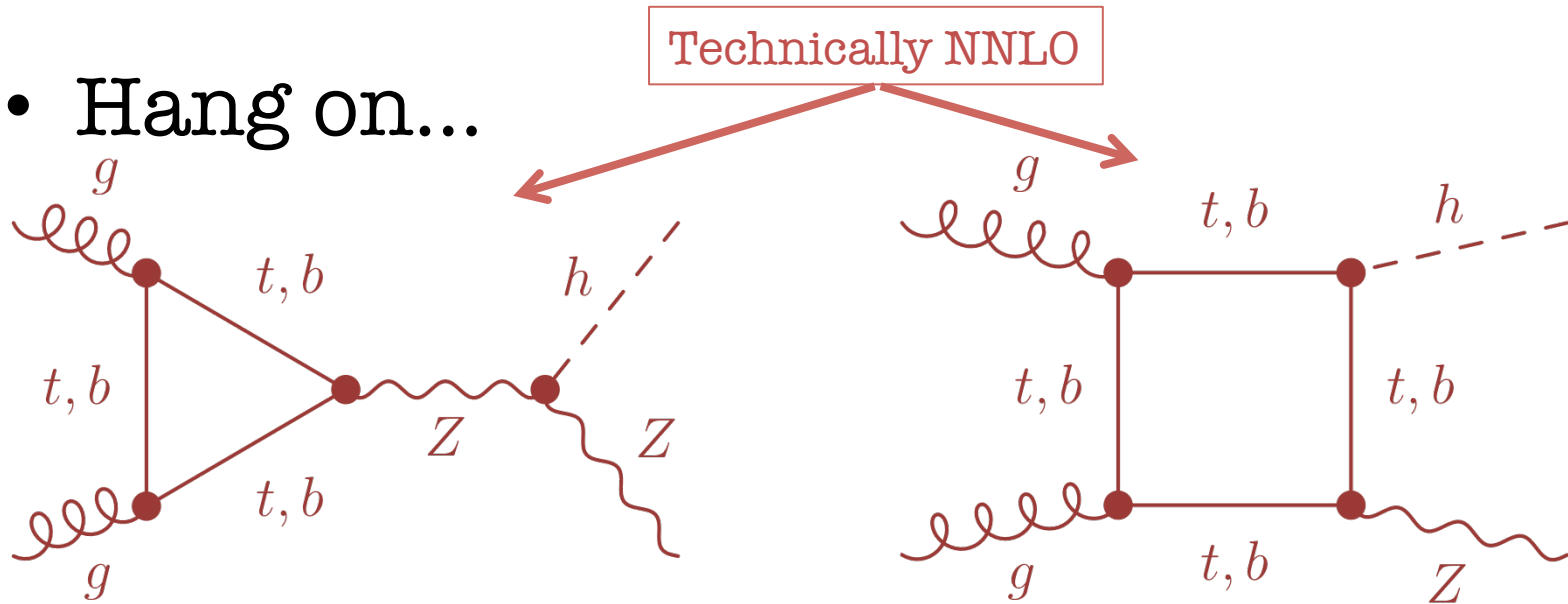- BSM NLO effects may be measurable.

SM@NNLO in Boosted Regime

- Certain searches rely on boosted Higgs
  - Boosted cuts, BDRS analysis (Butterworth, Davison, Rubin, Salam)

- Best example: $pp \to hZ$, $h \to \bar{b}b$

- Production:

$\left| \begin{array}{c} q \nearrow \qquad \qquad Z \\ \\ q \nearrow \qquad \qquad h \end{array} \right|^2 \propto c_V^2$
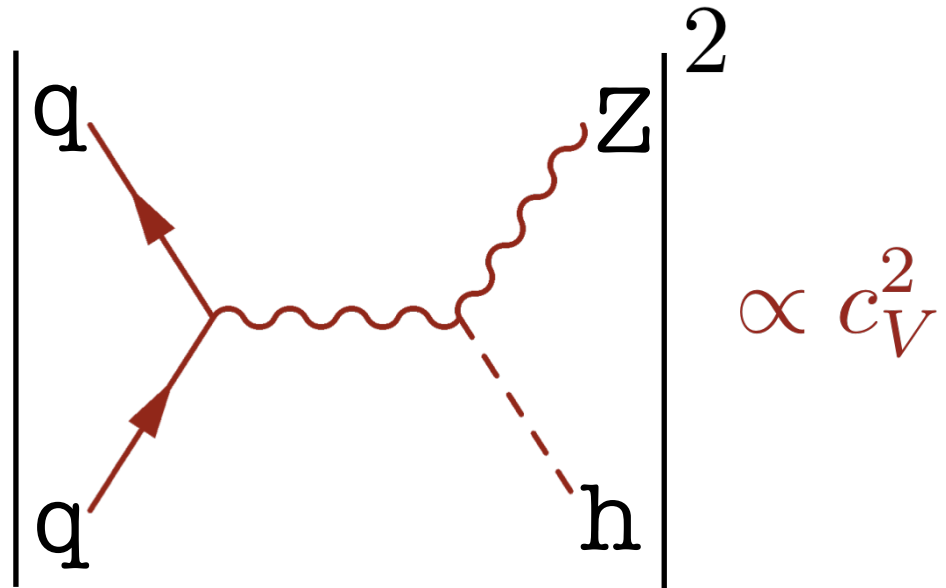
SM@NNLO in Boosted Regime

- Hang on...

Technically NNLO

- So what? This is a $10_{LO}+7_{NLO}$% effect.

- Currently: absorb into NNLO K-factor
  (Only for total cross section!)

SM@NNLO in Boosted Regime

- Is it a good idea to absorb gluon fusion into Drell-Yan K-factor, then apply boosted analysis?

- Typical scales in boosted analysis:

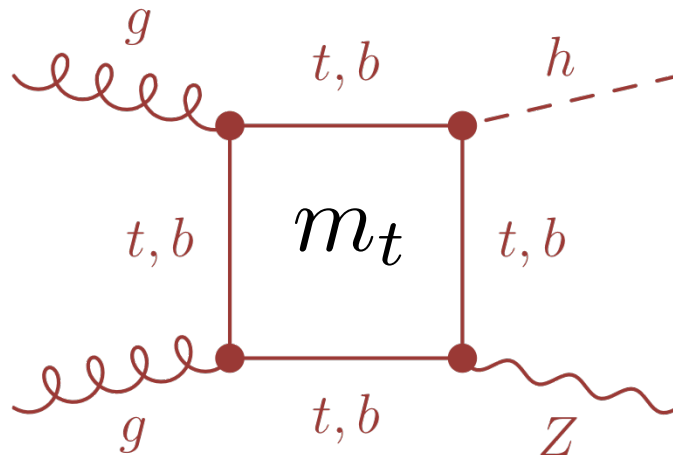$$p_{T,h} \gtrsim 150 \text{ GeV}$$

SM@NNLO in Boosted Regime

- Is it a good idea to absorb gluon fusion into Drell-Yan K-factor, then apply boosted analysis?
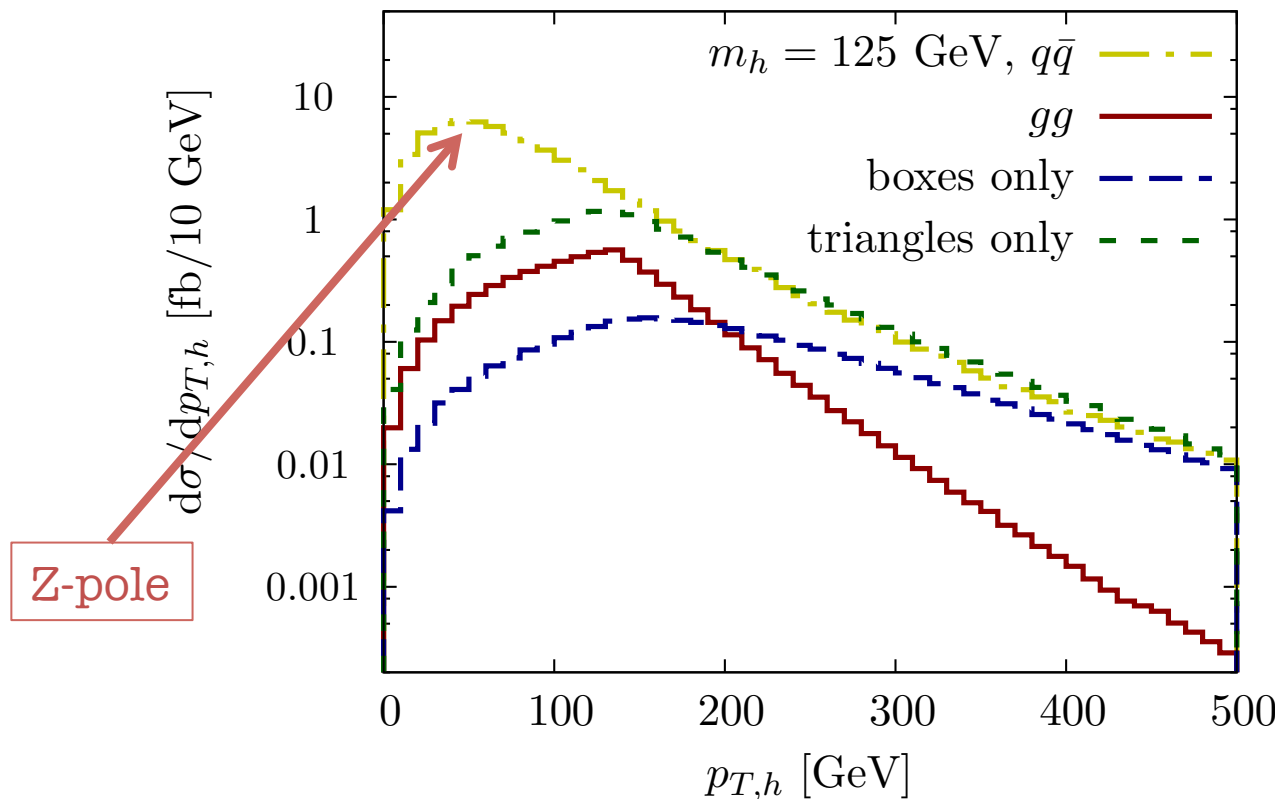
- Typical scales in Drell-Yan:
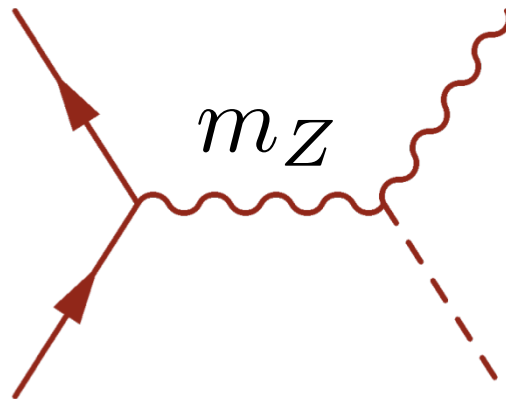
SM@NNLO in Boosted Regime

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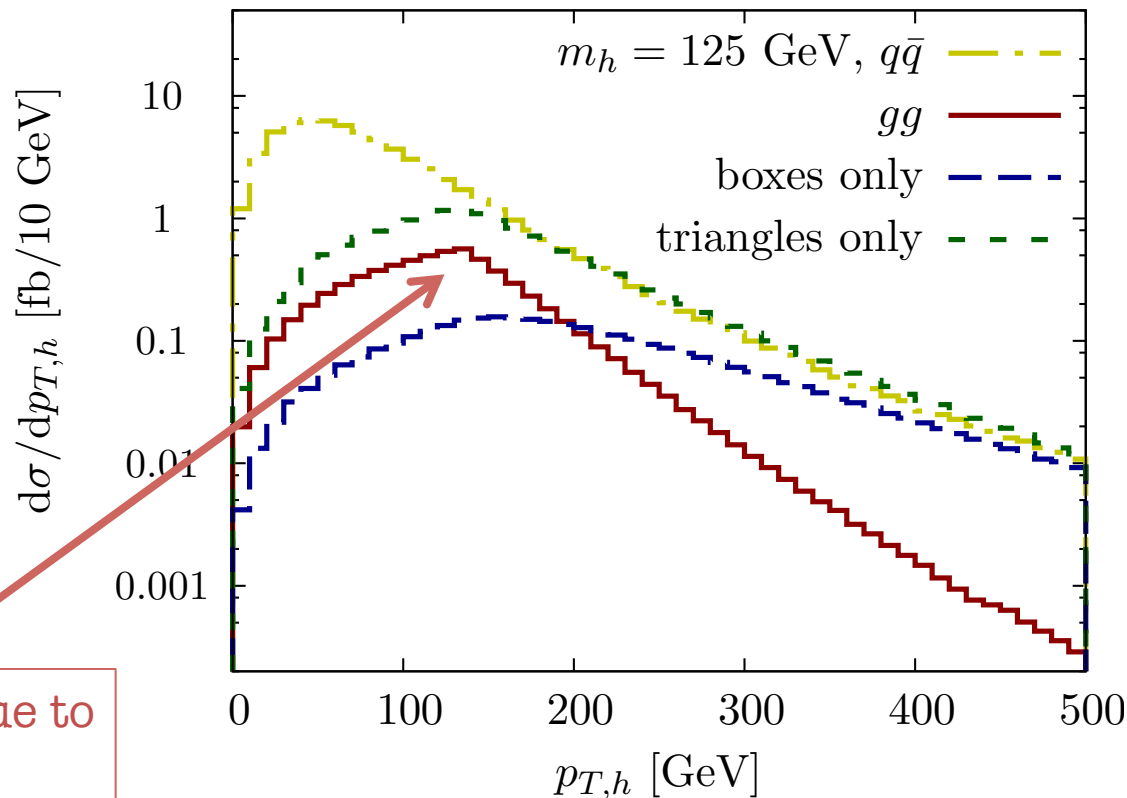
- Typical scales in gluon fusion:

SM@NNLO in Boosted Regime

- Drell Yan + Gluon fusion p_T distribution is not a re-scaled Drell-Yan distribution:

SM@NNLO in Boosted Regime

- Drell Yan + Gluon fusion p_T distribution is not a re-scaled Drell-Yan distribution:

Threshold due to Tops!
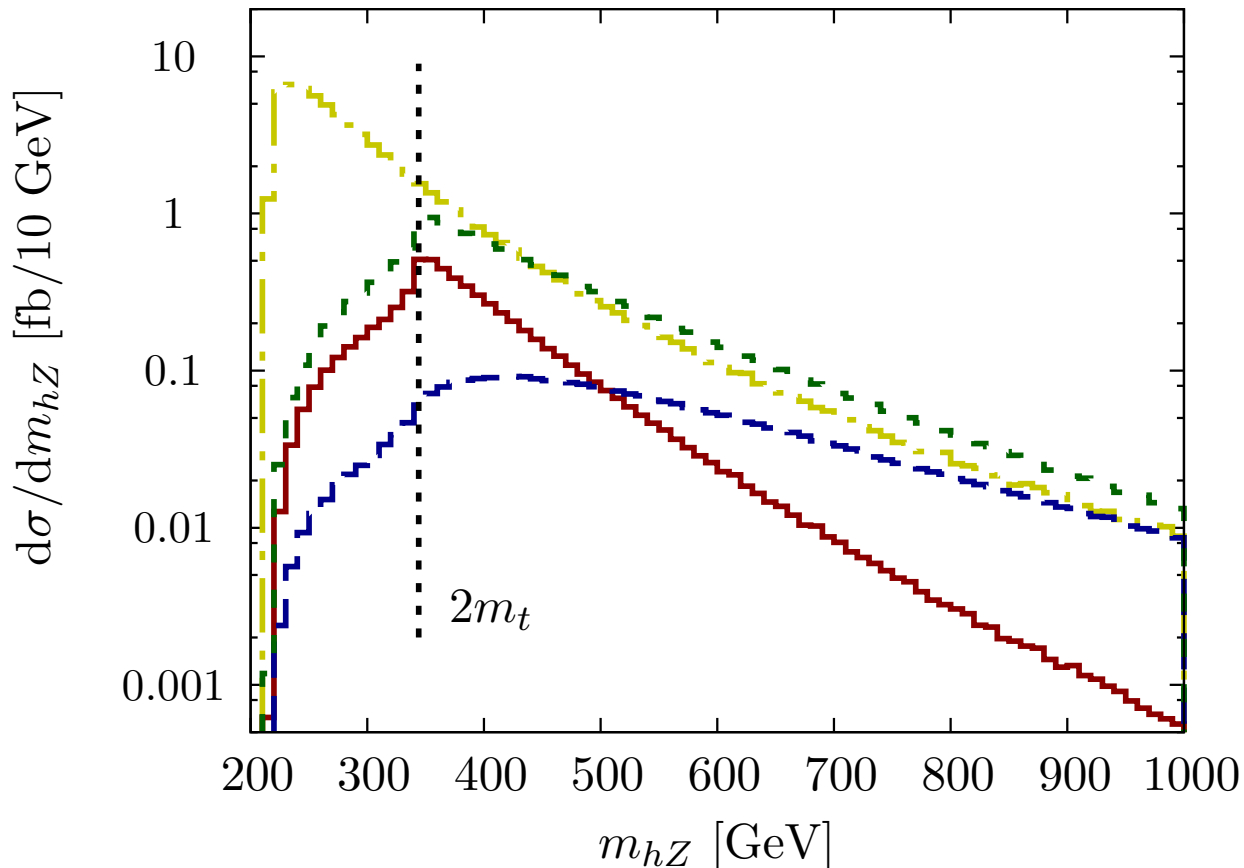
SM@NNLO in Boosted Regime

- Drell Yan + Gluon fusion p_T distribution is not a re-scaled Drell-Yan distribution:
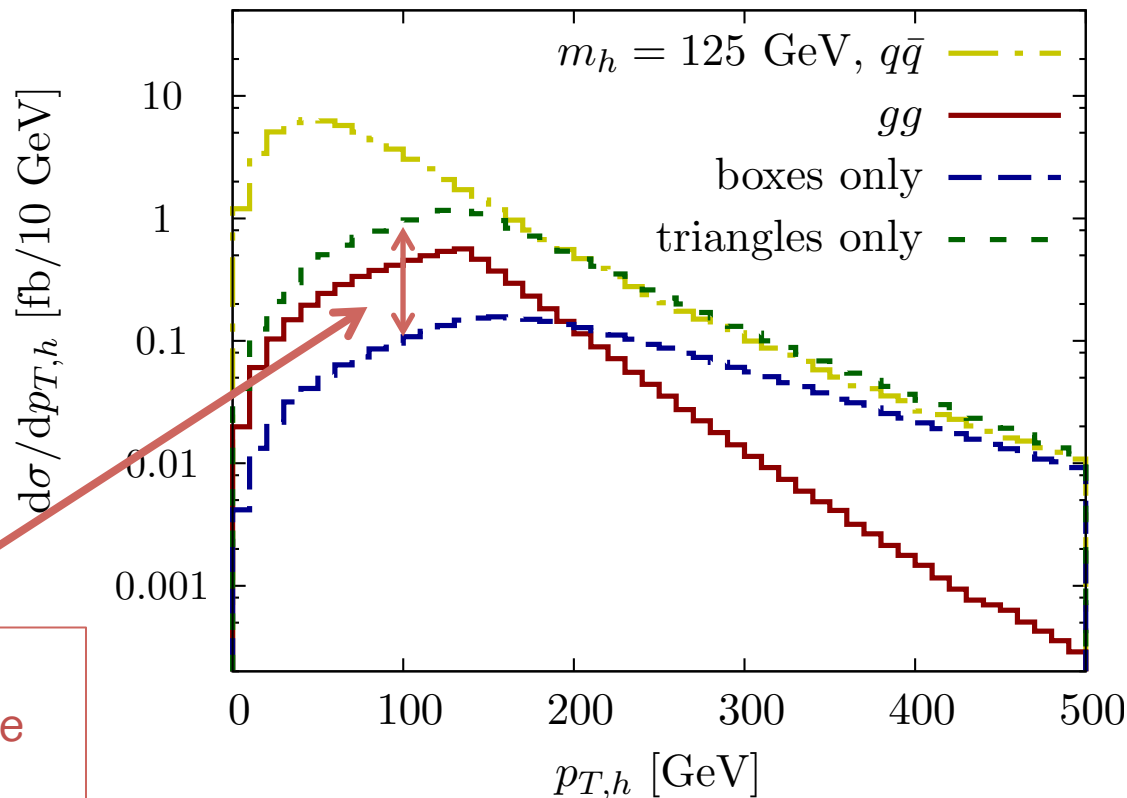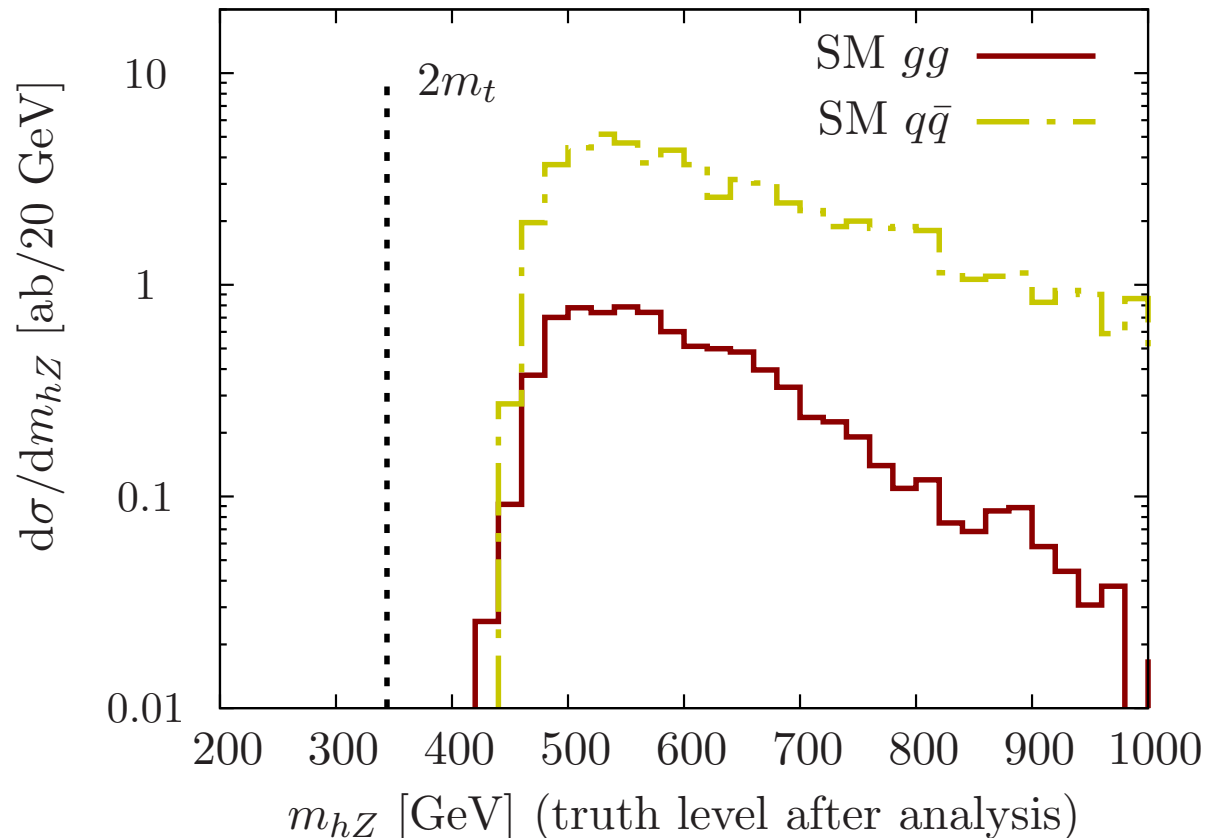

Triangles and boxes interfere in SM!

SM@NNLO in Boosted Regime

- In terms of invariant mass:

SM@NNLO in Boosted Regime

- After applying typical boosted cuts and BDRS substructure analysis:

SM@NNLO in Boosted Regime

- Is it a good idea to absorb gluon fusion into Drell-Yan K-factor, then apply boosted analysis? No!

- Ok for discovery data, but not ok for future data…

SM@NNLO in Boosted Regime

- If we denote the inclusive K-factor as

$$K_{\text{eff}} = \frac{K_{\bar{q}q}^{\text{NNLO}} \times \sigma_{\bar{q}q}^{\text{Inc}} + K_{gg}^{\text{NLO}} \times \sigma_{gg}^{\text{Inc}}}{\sigma_{\bar{q}q}^{\text{Inc}}}$$

- Then, by construction

$$\sigma^{\text{Inc}} = K_{\text{eff}} \sigma_{\bar{q}q}^{\text{Inc}}$$

- But, due to the different distributions

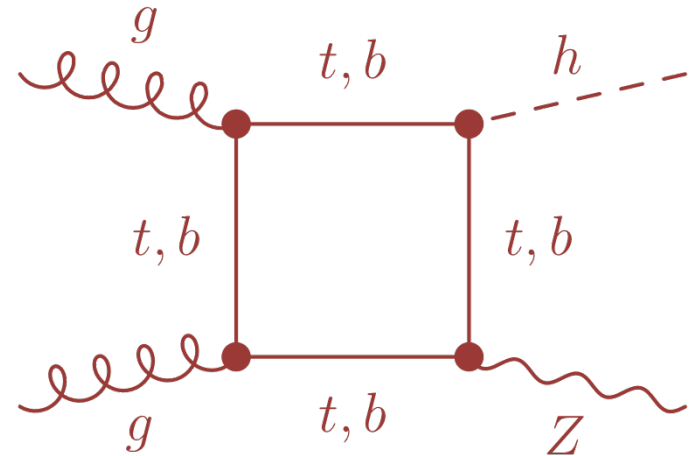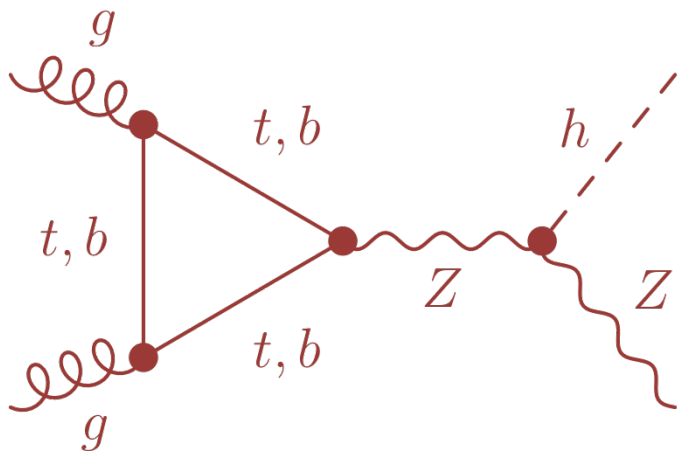$$\text{Cuts}[\sigma^{\text{Inc}}] \neq K_{\text{eff}} \times \text{Cuts}[\sigma_{\bar{q}q}^{\text{Inc}}]$$

- Should analyze Drell-Yan and gluon fusion separately...

SM@NNLO in Boosted Regime

- There are implications for SM Higgs searches.

- Full result gives 9% enhancement after typical p_T cuts.

- Full result gives 1% reduction after p_T cuts and BDRS.

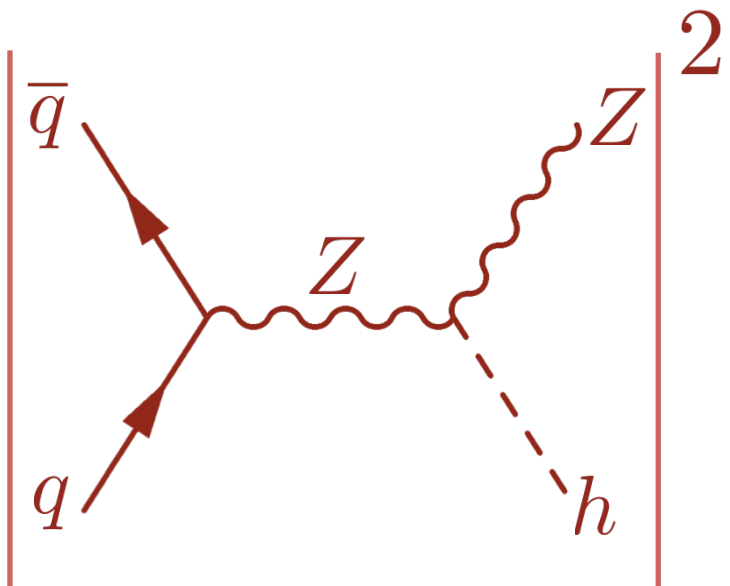- Quoted theory errors: 5.5%.

BSM@NNLO in Boosted Regime

- Returning to diagrams:

- Finite, as in $gg \to h$!

- BSM result: rescaled Higgs couplings
  – No ambiguities about counterterms...

BSM@NNLO in Boosted Regime

- Naïvely:

$$\sigma(pp \to hZ) \sim \left| \begin{array}{c} \bar{q} \\ \\ q \end{array} \quad Z \quad \begin{array}{c} Z \\ \\ h \end{array} \right|^2 \propto c_V^2$$

BSM@NNLO in Boosted Regime

- Reality:

$$\sigma(pp \to hZ) \sim \left| \begin{array}{c} \includegraphics \end{array} \right|^2 +$$

$$\left| \begin{array}{c} \includegraphics \end{array} \right|^2$$

$$\sim c_V^2 + f(c_V, c_t, c_B)$$

BSM@NNLO in Boosted Regime

- ## Also keep in mind:

Triangles and boxes interfere in SM!
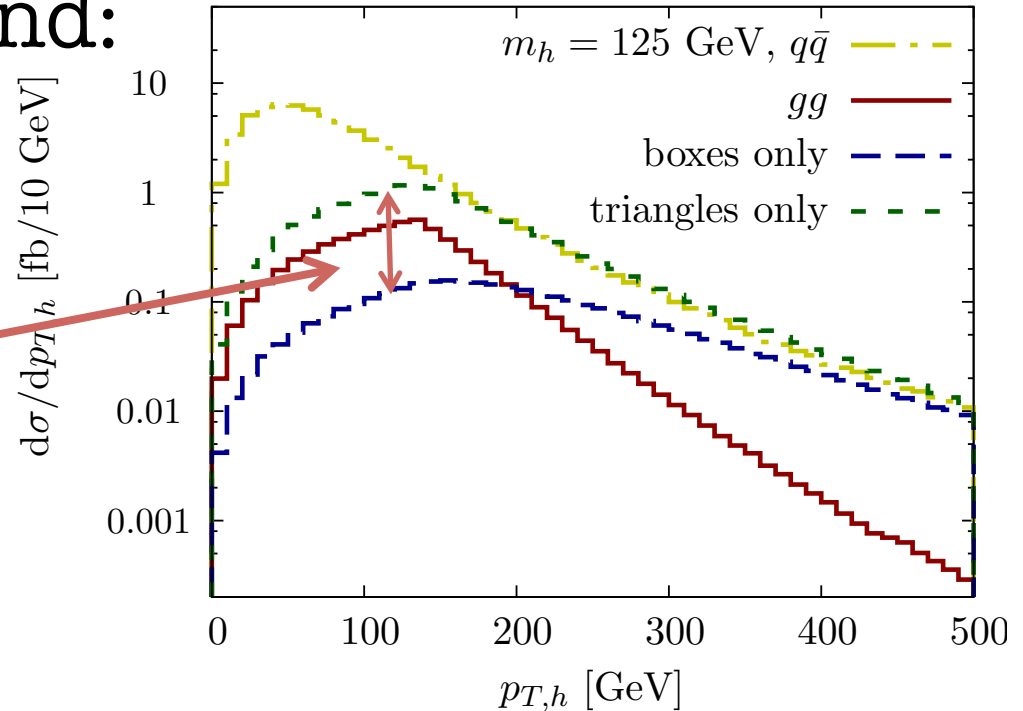
- ## BSM Higgs couplings may spoil interference, enhancing gluon fusion!

BSM@NNLO in Inclusive Rate

- Naïve result:

$$R \equiv \frac{\sigma_{\mathrm{BSM}}}{\sigma_{\mathrm{SM}}} = c_V^2 = (1 + \delta_V)^2$$

- Full result at inclusive level:

Weak dependence on top coupling.

$$R_{\mathrm{Inc}} = 1 - 0.14\delta_t + 0.06\delta_t^2$$
$$- 0.26\delta_t\delta_V + 2.14\delta_V + 1.20\delta_V^2$$

Similar to LO scaling

BSM@NNLO in Boosted Regime

- Naïve result:

$$R \equiv \frac{\sigma_{\mathrm{BSM}}}{\sigma_{\mathrm{SM}}} = c_V^2 = (1 + \delta_V)^2$$

- Full result after boosted cuts and BDRS:

Much stronger dependence on top coupling.
Boosted cuts "pull-out" boxes and triangles.

$$R_{\mathrm{BDRS}} = 1 - 0.42\delta_t + 0.52\delta_t^2$$
$$- 1.46\delta_t\delta_V + 2.42\delta_V + 1.94\delta_V^2$$

BSM@NNLO in Boosted Regime

- BSM searches at the 14 TeV LHC?
  - BSM Standard Candles:
    - Higgs portal? Universal re-scaling, nothing new
    - Type II 2HDM (SUSY etc)
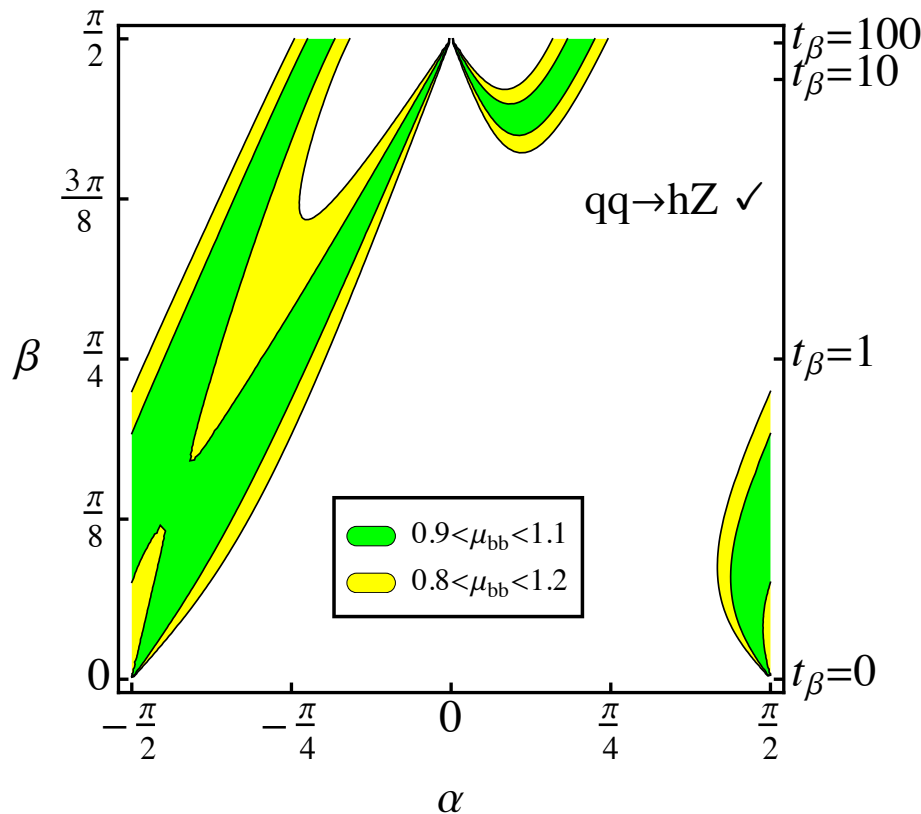
$$c_V = \sin(\beta - \alpha)$$

$$c_t = \cos\alpha/\sin\beta$$

$$c_b = -\sin\alpha/\cos\beta$$
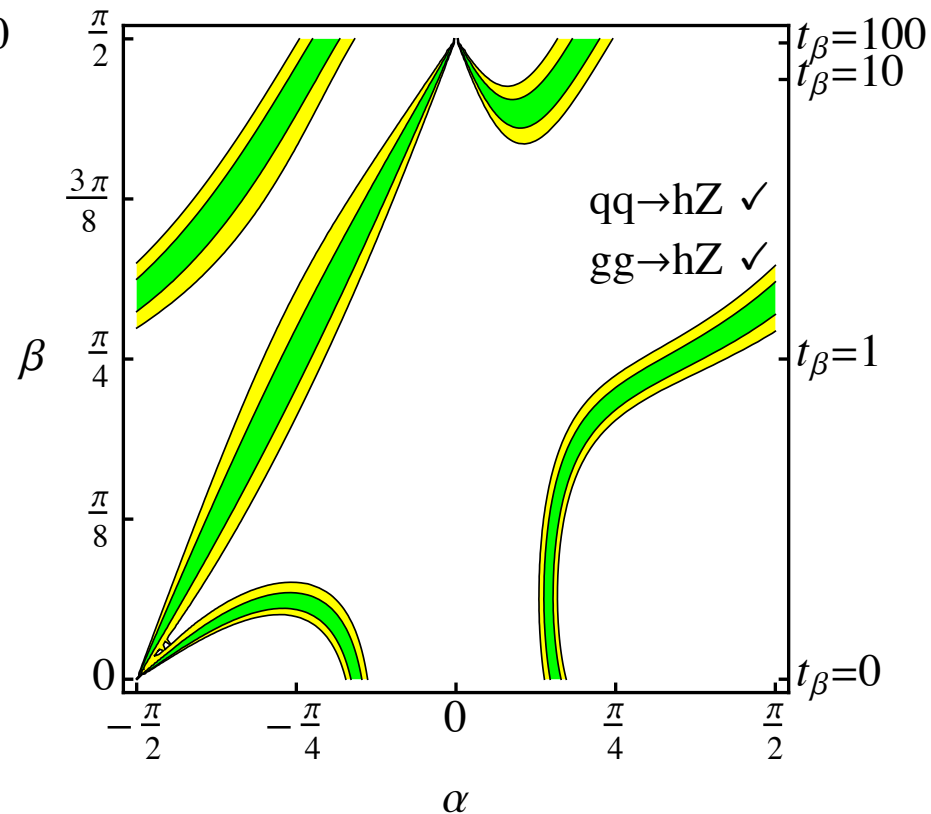
- Re-scaled: $\sigma(pp \to hZ)$, $\mathrm{BR}(h \to \bar{b}b)$

BSM@NNLO in Boosted Regime

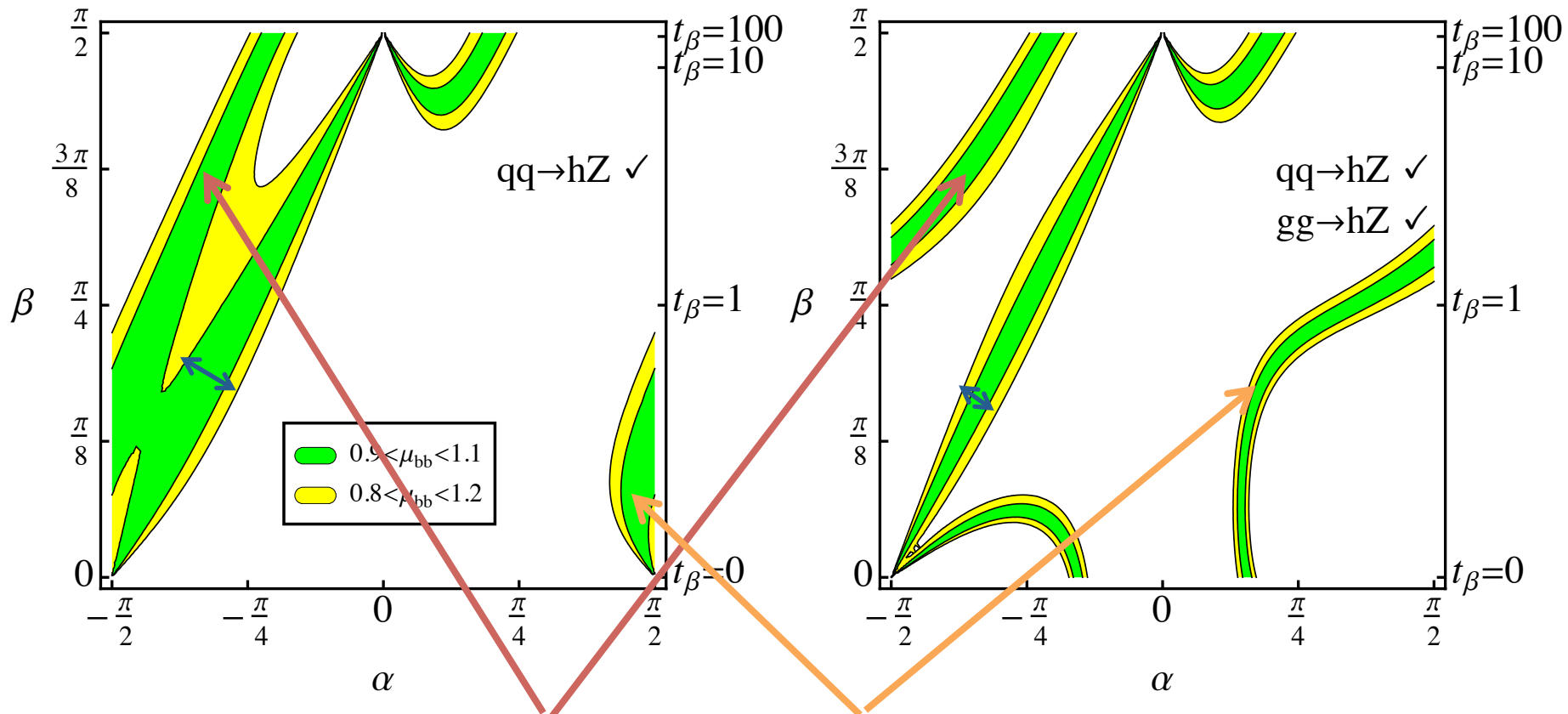- ## Type II 2HDM Results:

Naïve Rescaling

Full Result

BSM@NNLO in Boosted Regime

- ## Type II 2HDM Results:

Significant differences! Gluon fusion component clearly important!

BSM@NNLO in Boosted Regime

- Why the differences?
- Due to unitarity, typically $c_V \leq 1$
  - LO implies:

$$\sigma(pp \to hZ) \leq \sigma_{\mathrm{SM}}(pp \to hZ)$$

This is an artificial restriction due to LO assumption!

  - With gluon fusion included there is no restriction, especially if c_t altered!

- SM box vs triangle cancellation spoiled if modified couplings giving large effects!

LHC Higgs Summary

- ## SM:

  - Higgs precision: revisiting NLO distributions may reveal interesting features

- ## BSM:

  - LO assumptions: Ok for discovery data, but may misinterpret or overlook BSM Higgs signals in future data!

  - Precision BSM will require NLO calculations

  - Demonstrated here in boosted 2HDM

Toward a Precision Higgs Era

- Higgs:
  - Unique opportunity to confront fundamental questions about nature.

- In practice:
  - Keep an open mind to all possibilities:
    - Nice Higgs: BSM at LO
    - Ambivalent Higgs: BSM at NLO
    - Nasty Higgs: SM at all orders.

- Prepare to confront any outcome, leave no stone unturned…

Toward a Precision Higgs Era

- Higgs:
  - Unique opportunity to confront fundamental questions about nature.

- In practice:
  - Keep an open mind to all possibilities:
    - Nice Higgs: BSM at LO
    - Ambivalent Higgs: BSM at NLO ← This work only scratches surface!
    - Nasty Higgs: SM at all orders.

- Prepare to confront any outcome, leave no stone unturned…